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RESIDUAL SOIL PHOSPHORUS IN TROPICAL OXISOLS: AN OPPORTUNITY TO
ENHANCE FERTILIZER USE EFFICIENCY?

A Thesis Presented

by

Lauren P Bomeisl

to

The Faculty of the Graduate College

of

The University of Vermont

In Partial Fulfillment of the Requirements
for the Degree of Master of Science
Specializing in Natural Resources

October, 2019

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Thesis Examination Committee:

Eric Roy, Ph.D., Advisor
Joshua Faulkner, Ph.D., Chairperson
Gillian Galford, Ph.D.
Cynthia J. Forehand, Ph.D., Dean of the Graduate College

ABSTRACT

Phosphorus (P) is essential to life on Earth and often the limiting nutrient in agricultural systems. P fertilizer is thus an essential resource to maintain food security. In the last half century, agricultural intensification has led to an increase in P fertilizer consumption from 4.6 to 17.5 Tg of P/year to meet rising global food demand. Mineral P (i.e., phosphate rock) is a non-renewable resource in the context of the Anthropocene, and its price is vulnerable to global market fluctuations. Increased efficiency of P use on farms is considered the most effective strategy to conserve P. The soybean industry demands 9.7% of global P use, of which Brazil's soy industry consumes the most, accounting for 5.8% of the world's P_2O_5 use in 2014. This global source of soy production is challenged by the unique tendency of weathered tropical soils, such as Oxisols, to retain (i.e., fix) P in forms that are unavailable to crops. The accumulation of soil P due to years of P fertilization in excess of harvested P is referred to as "residual" or "legacy" P. Historical hotspots for crop production in the US and Europe have relied on residual soil P stocks to maintain yields despite reduced P inputs. Whether Brazil will be able to utilize the same strategy depends on the accessibility of residual soil P stocks when applied fertilizer P is reduced. Field research on this topic remains relatively scarce for cultivated Oxisols in tropical climates. I conducted a field trial at Tanguro Ranch in Mato Grosso, Brazil on a field that has been fertilized at standard high rates for 10 years to test whether residual soil P can be accessed by soy crops. Soy yield response differed significantly ($p < 0.05$) based on the interaction between fertilization treatment (0%, 50%, or 100% of standard P fertilization) and soil texture. My results highlight opportunities to enhance P fertilizer use efficiency in intensive tropical agriculture.

DEDICATION

This Master's thesis is dedicated to womxn around the world who work tirelessly to grow food, nurture their families, and build community despite adversity.

ACKNOWLEDGEMENTS

This project would not have been possible without the following folks: Dr. Stephen Porder at Brown University whose expertise built a path for this work, Dr. Chris Neill - the fearless field scientist from Woods Hole Research Center with boundless experience, and the incredibly passionate IPAM crew at Tanguro ranch who provided strength, insight, and laughter in times of need. I received much encouragement and perspective from my committee members, Gillian Galford and Joshua Faulkner, who helped me view this project through an agronomic lens and provided much-needed insight that can only be gleaned from experience. I have the utmost gratitude and admiration for my advisor and mentor, Dr. Eric Roy, whose unconditional support provided a much-needed balance that propelled this work forward. Dr. Roy's dedication to nutrient cycling has instilled a sense of inspiration in me that has nurtured my relationship with agriculture and provided me a sense of purpose as a scientist. A special thanks to Hillary Sullivan and Dr. Leandro Maracahipes who provided incredible support and friendship during the harvest season, and of course, I'd like to acknowledge my sweet pup Kavi for demanding I take breaks to get outside, exercise, and snuggle.

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CHAPTER 1. INTRODUCTION & COMPREHENSIVE LITERATURE REVIEW

1.1. Background and Regional Context

Phosphorus (P) is often the limiting nutrient required to close yield gaps (McDowell et al., 2016) and therefore an essential resource to maintain global food security. In order to meet accelerating global food demand, P fertilizer consumption has increased from 4.6 to 17.5 Tg P yr⁻¹ in the last half century (Lu & Tian, 2017). This magnitude of change in global P consumption is an outcome of agricultural intensification, including the increase of nutrient inputs per unit cropland area, which rose from 4 to 12 kg P ha⁻¹ yr⁻¹ on average for all crops globally during the same period (Lu & Tian, 2017). Recent trends in agricultural intensification have led to a shift in mineral P consumption from the global north (i.e., the US and Europe) to the global south (i.e., southern China, northern India, and Brazil), primarily for the production of wheat, maize, soybean, rice, and oil palm (Lu & Tian, 2017).

This global trend toward intensified production in the tropics is challenged by the unique tendency of weathered tropical soils to retain (i.e., fix) P in a form that is regarded as unavailable for plant uptake (Ker et al., 1996; Filho & Torrent, 1993; Hughes & Le Mare, 1982). The additional P input per hectare required to close yield gaps on P-fixing soils has economic as well as environmental implications for the sustainability of agricultural trends with regard to mineral P consumption (Mahon et al., 2018; Hunter et al., 2017; Roy et al., 2016). The surplus P that accumulates in the soil, i.e., the unused

“residual P” or “legacy P” stock, is believed to become available over time and provide a secondary source of P that may supplement future fertilization (Sattari et al., 2012).

The soybean industry demands 9.7% of global P use, of which the largest P consumer is the Brazilian soybean industry, accounting for 5.8% of the world’s P_2O_5 use in 2014 (IPNI and IFA, 2017). Soy cropland in Brazil is sprawled across former Amazon rainforest and Cerrado savannah, the latter of which is a lesser known and undervalued hotspot of biodiversity of global importance (Klink and Machado, 2005). The majority of land developed for soy production was previously unplanted and unfertilized pastureland in the Cerrado. Soy conversion did not substantially increase the decline of this type of pastureland, but rather replaced the less intensive conversion from unplanted to planted pastureland (Dias et al., 2016). Though damaging to the valuable microdiversity of a globally cherished biome, intensification of the Cerrado has offered an alternative to deforestation of the Amazon that would otherwise have more severe and long-term implications for global climate change (Galford et al., 2010). Moving forward, conservation of remaining Amazon and Cerrado ecosystems is a critical task. Some have argued that intensification of existing croplands (including increasing yields via increased fertilization) can help mitigate expansion of agriculture further into natural ecosystems (Macedo et al., 2012).

The proliferation of P consumption to fuel intensification in Brazil is a productionist strategy, criticized by holists for lacking to address systemic, socio-economic challenges associated with food insecurity (Godfray, 2015; Kuyper and Struik, 2014). Holists who reject intensification as a sustainable approach suggest that

agroecological models can be scaled up to meet rising food demands (Rockstrom et al., 2017). Supporters of intensification argue that this alternative would likely lead to extensification, or the expansion of agricultural land, resulting in greater forest loss, GHG emissions, and threats to biodiversity (Godfray and Garnett, 2014; Tilman et al., 2011). With regard to concerns raised over developing previously preserved land in the Amazon and the Cerrado, intensification in Brazil has enabled the nation's soy production to rise from 1.7 t ha⁻¹ in 1990 to 2.9 t ha⁻¹ in 2012 despite the decreasing rate of agricultural expansion (Dias et al., 2016). For Brazil's soy industry, intensification is considered the most sustainable (and necessary) strategy to increase production while reducing the rate of deforestation (Macedo et al., 2012). Despite initially rapid expansion in which developed cropland more than doubled from 2001 to 2006 to cover about 100,000 km² (Galford et al., 2010), intensification via land conversion, double cropping and increased fertilization rates has afforded the decoupling of soy production and deforestation in the Amazon since 2006 (Macedo et al., 2012).

Historical hotspots for crop cultivation in the north (i.e., the Midwestern US and Western Europe) have achieved higher rates of P use efficiency in recent decades, maintaining yields while substantially reducing P inputs. Moderation of mineral P consumption is afforded by the accessibility of “residual P” after years of soil P accumulation. Whether tropical producers will be able to utilize a similar approach is ultimately dependent on soil P dynamics that are expected to change over time (Roy et al., 2016). The tropics have accumulated the greatest residual P stock as a consequence of the poor P use efficiency of cultivated P-fixing soils (MacDonald et al., 2011). Roy et al.

(2016) calculated annual accumulation of residual P stocks would be 1-4 Tg P yr⁻¹ if all 2005 cropland areas on P-fixing soils were under intensive production. Further, this rate would double by 2050 due to anticipated extensification (e.g., in Africa). Rapid increase of nutrient consumption in tropical agriculture presents many unknowns regarding global nutrient flows (Cordell & White, 2014; Samora, 2018), most notably, the ecological implications of unprecedented demand for and application of mineral P fertilizer (Roy et al., 2016; Groppo et al., 2015).

1.2. Literature Review

In light of recent agricultural intensification in the tropics, concerns have been raised regarding environmental degradation associated with deforestation. Studies in the Amazon region of Mato Grosso have shown that the risk of eutrophication or excessive nutrient loading is negligible compared to the impact of soy intensification in temperate ecosystems (Neill et al., 2013; Riskin et al., 2017). These findings agree with previous observations that found Mato Grosso soils to be well buffered against the risk of erosion during storm events due to high infiltration rates under cultivated soy and the deep soil profile of this region (Scheffler et al., 2011). Annual water yield from a small watershed was reported to quadruple after conversion to soy from forest, but the relative contribution from base flow (~95%) remained unchanged (Hayhoe et al., 2011). Neill et al. (2013) forewarns the potential for cumulative watershed impacts of deforestation at a larger scale under scenarios of extensification, a concern that further suggests intensification to be the more sustainable approach to increasing tropical production.

The sustainability of nutrient management on heavily weathered, P-fixing soils remains unknown, though the pedogenesis and consequential characteristics that result in P-fixation are well understood by geochemists. The affinity to fix P, or P sorption capacity, is attributed to the prevalence of Al and Fe oxides, as well as their clayey texture, or colloidal content (de Campos et al., 2016; Fischer et al., 2018; Oliveira et al., 2018; de Sousa and Lobato, 2003). Oxisols are characterized as rich with Fe and Al oxides, or rather the relative lack of base cations, such as K, Na, and Ca, that are stripped via hydrolysis and leached under heavily weathered conditions. This process also breaks down rock to increase the relative clay content of the soil, another characteristic of Oxisols that is considered synonymous with Fe and Al oxide content as both characteristics are a direct consequence of weathering (Palm et al., 2007). Oxisols are defined by U.S. Taxonomy as the most heavily weathered soil, typically found on older landscapes in tropical, humid climates that undergo greater rates of weathering compared to temperate or arid climates (Jenny, 1994).

The potential to sustainably close yield gaps on P-fixing soils in the tropics depends on the rate of increase of the bioavailable P pool, commonly indicated by soil test P (STP) metrics. Decades-long accumulation of residual P has been demonstrated to act as a P source under temperate conditions in the absence of standard fertilization (Table 1.1). Based on the accumulation of STP over time under fertilization, Roy et al. (2017) forecasted it could be up to a century before some soybean farmers in Mato Grosso may achieve a more balanced nutrient budget on finer textured Oxisols. The bioavailability of residual P in temperate regions has been validated based on yield

response to varying P treatments and nutrient management recommendations have consequently been framed with respect to estimations of critical STP thresholds across variable scales, soils, crops, and climates (Table 1.1). Long-term soybean field trials in temperate regions have concluded that STP values are more indicative of yield response than the degree of P treatment (McCollum, 1991; Dodd and Mallarino, 2005). Dodd and Mallarino (2005) found little to no significance between yield responses to variable P treatments, except for zero P fertilization applied to soils that had initial STP values near or below the identified critical STP range (12.4-20.8 mg P kg⁻¹ soil). This result followed McCollum's results that concluded yield response depended primarily on initial STP in relation to a critical threshold, identified as 22 g m⁻³ (or 20 mg P kg⁻¹ based on soil bulk density of 1.1 Mg m⁻³), and that STP values greater than 55 g m⁻³ (i.e., 50 mg P kg⁻¹) revealed an increased rate of P loss from the bioavailable P pool to the residual P pool.

Soil test P metrics such as Mehlich P-1, Bray-1 P, and Olsen P do not capture a consistent proportion of bioavailable P across variable soil textures (Schlindwein et al., 2011; Bortolon et al., 2011; de Silva and Raij, 1999).

Recommendations for nutrient management based on STP thresholds are therefore classified based on texture class (de Sousa and Rein, 2011). Though STP has proven to be indicative of thresholds for maximum yield, the role of residual P following the cessation of P fertilization is not fully realized by STP analyses alone (Sattari et al., 2012). The relationship between high Fe, Al oxide content, low Si oxide content, and remaining sorption capacity demonstrated by Roy et al. (2017) suggests that a relevant indicator for residual P availability in tropical soils could be soil bulk chemistry. Al and

Fe oxides (the sum of which is termed R_2O_3) are commonly used as a proxy for clay content, though other findings have emphasized mineral quantity and type to be more relevant indicators of a soil's capacity to adsorb P than texture (Ker et al., 1996).

Similarly, a study done by Oliveira et al. (2018) revealed texture to have no significant impact on yield when fertilized beyond a critical STP threshold defined based on P sorption capacity.

The increasing accessibility of residual P is not exclusively afforded by recurring fertilization; indicators of soil fertility such as organic matter (OM) and cation exchange capacity (CEC) have been observed to influence P sorption (and desorption) mechanisms in tropical agriculture. Some studies suggest the presence of organic matter (OM) can reduce the remaining P sorption capacity of Oxisols (McDowell et al., 2001) and increase the rate of P bioavailability (Eichler-Löbermann et al., 2007). P fractionation methods employed by Maranguit et al. (2016) resolved that easily available P fractions correlated with carbon content. Others suggest that the presence of OM may actually increase the area for sorption due to an increase in colloid content, counteracting the impact of OM sorption site occlusion on remaining sorption capacity (de Campos et al., 2016; Abdala et al., 2014). Though advantageous for P availability (Rosa et al., 2019), the incorporation of organic fertilizers into large-scale agriculture could increase the risk of leaching (Dodd and Sharpley, 2015). Regardless of the trade-offs in utilizing organic P sources, residual P is believed to be the most viable P source for intensification in Brazil after mineral P (Cordell et al. 2012; Withers et al., 2017).

Based on agronomic field trials previously conducted, we know that residual P accumulates and remains in the plow layer (Rodrigues et al., 2016; Gallet et al., 2003; Riskin et al., 2013). Tropical soil studies have found residual P to be stored over time in both labile (readily bioavailable) and stable (unavailable) P pools, the latter of which is associated with a high concentration of Al and Fe hydroxides. Though Al and Fe oxides in tropical soils act as a P sink initially, we expect that this accumulated soil P stock will eventually act as a long-term source for bioavailable P (Ghosh et al. 2011).

Recommendations made by researchers at EMBRAPA suggest texture specific critical STP thresholds, beyond which, fertilization rates can be reduced (to 50% of the standard rate) for fertility ‘maintenance’ rather than ‘correction’ (de Sousa & Rein, 2011). Given the accumulation of residual P after several decades of soy cultivation in Mato Grosso (Roy et al., 2016), now is an opportune time for Mato Grosso to trial refined P management strategies informed by soil characterization. Tropical soils research focused on fertility must be framed to highlight relationships that are meaningful for farmer application and should therefore be specific to regional context and ecological conditions (Sanchez et al., 2003; Bruulsema et al., 2019).

Agronomic field trials have been conducted in Brazil on Oxisols of greater sand content (70-80%), representative of soils with more inherent P availability in the Cerrado in early stages of development (Mariussi et al., 2019; da Costa et al., 2017; dos Santos et al., 2015). These studies do not does not fully encapsulate the relevant landscape historically under soy cultivation in Mato Grosso, nor do they offer an assessment of P treatments between 0 and 100% of the standard rate applied in Mato Grosso (~90 kg P₂O₅

ha⁻¹). More research is needed to provide much needed perspective on the potential for long-term access to residual P in stable P pools associated with high clay content.

There is limited field research that has explored whether accumulated residual soil P stocks can provide a sustainable P source for intensified tropical agriculture, and a limited range of textures and treatments that have been trialed to demonstrate prospects for reduced or zero P application after at least a decade of soy cultivation. The goal of this thesis was to build upon previous work to inform P management opportunities based on soil conditions common to tropical agriculture, and to highlight connections between soil fertility and land use history that are relevant to major producers in this region.

Study	Treatments (kg P ha ⁻¹)	Yrs	Critical STP (mg P kg ⁻¹)	STP test	Fertilization significance	Treatment significance
Mallarino, Webb, Blackner, 1991	0, 11.2, 22.4, 33.6	14	~20	Bray P-1	none	None
McCallister et al., 1987	0, 11, 22, 33	12	15 (corn) and 22 (wheat)	Bray P-1	None	none
Fulford and Culman, 2018	0, 15.7, 31.3	9	21	Bray P-1	2/9 years	none
McCullum, 1991	0, 20.1, 40.6, 59.8	26	~22	Mehlich-1	none	none
Zicker et al., 2018	0, 22, 44	13	n/a	calcium acetate/lactate	none	none
Dodd & Mallarino, 2005	0, 22, 44	27	20	Bray P-1	18/81 trials	1/81 trials
Oliveira et al., 2018	0, 1, 6, 12, 24% of PAC	1	16-21 % PAC	Mehlich-1	n/a	n/a

Study	Soil type(s)	Climate	Crop Type	Regional	Field	Lab
Mallarino, Webb, Blackner, 1991	Typic Haplaquoll	Temperate	corn/soy	x	x	-
McCallister et al., 1987	Mollisols	Temperate	corn/wheat	x	x	-
Fulford and Culman, 2018	Aquic Fragiudalf, Mollic Epiaqualf, Typic Argiaquoll	Temperate	corn/soy	x	x	-
McCullum, 1991	Typic Umbraquilt	Temperate	corn/soy	-	x	-
Zicker et al., 2018	Stagnic Cambisol	Temperate	beet/wheat/barley	x	x	-
Dodd & Mallarino, 2005	Aquic & Typic Hapludolls, Typic Endoaquolls,	Temperate	corn/soy	x	x	-
Oliveira et al., 2018	Red-yellow Latosol and Typic Hapludalf	Greenhouse	soy	x	-	x

Table 1.1 Yield trials of staple foods previously conducted in temperate regions that define critical STP

CHAPTER 2. SOYBEAN YIELD RESPONSE TO REDUCED PHOSPHORUS INPUTS AFTER TEN YEARS OF SURPLUS FERTILIZATION ON BRAZILIAN OXISOLS

2.1 Introduction

Phosphorus (P) is essential to life on Earth and commonly a limiting nutrient in agricultural systems (Elser, 2012). Given the geologic timeframe required for the regeneration of mineral P reserves, mineral P (i.e., phosphate rock) is a non-renewable resource in the context of the Anthropocene (Smil, 2000) and its price is vulnerable to fluctuations (Mew, 2016; Cordell & White, 2014). Though a multitude of innovative strategies exist to recover P from waste streams, increased P use efficiency on farms (and consequent reduction in P fertilizer demand) is considered a critical leverage point for conserving P resources and limiting the P-influenced eutrophication of surface waters (Roy, 2017; Cordell et al 2012).

After years of P fertilizer (and in some cases manure) inputs, producers of staple crops (e.g., soy, corn) in the Global North have been able to reduce P fertilization rates without compromising yields during the last several decades, afforded by the stock of residual P (also referred to as “legacy P”) accumulated in the soil (Sattari et al., 2012; Riskin et al., 2013a; Roy et al., 2016). Accumulation of residual P in soil is a function of the imbalance between fertilizer inputs and crop harvest outputs, as well as factors that determine whether the P will remain in place, including the soil’s P sorption capacity and local transport phenomena (Rowe et al., 2016). The 4R nutrient stewardship approach,

which advocates right source, right rate, right time, and right place of P application to soils, can be used to reduce excessive fertilizer use and capitalize on existing residual soil P stocks (Bruulsema et al., 2019). In the tropics, highly weathered soils rich in Fe and Al (e.g., Oxisols) are often characterized by a large capacity to sorb (or “fix”) P, decreasing its availability to crops (de Sousa and Lobato, 2003; Roy et al., 2016). The degree to which those farming such soils can adopt a 4R strategy characterized by reduced P fertilization and increased reliance on residual soil P without compromising yields, similar to producers in North America and Europe, remains unclear.

Brazil is a critical location to investigate the potential for producers in the tropics to harness residual soil P, given the country’s important role in the global food system and widespread high P-fixing soils (Roy et al., 2016; Withers et al., 2018). Within Brazil, soybean production accounts for 56.7 % of P fertilizer use (IPNI and IFA, 2017). Recent research in Brazil has indicated the following:

- Surplus P fertilization, e.g., annual P fertilizer inputs to soil that are double the amount of P harvested in soybean crops, remains widespread regardless of years in production or soil texture (Roy et al., 2016; Roy et al., 2017; Withers et al., 2018).
- The stock of residual soil P is growing at farm, state, and national levels, with the majority of residual P associated with Al- and Fe-oxides. Up to approximately one quarter of the increase in total soil P is accounted for by P forms thought to be potentially labile (Riskin et al., 2013b; Rodrigues et al., 2016; Roy et al., 2017; Withers et al., 2018).

- The accumulating residual P in Oxisols studied is present within the surface 20 cm of soil (i.e., within the plow layer) (Riskin et al., 2013b; Roy et al., 2017).
- Soil P sorption capacity in this same layer is declining slowly over time with surplus fertilization, but in some cases remains relatively high even after three decades (Roy et al., 2017).

Withers et al. (2018) point out that the major barrier to the use of residual soil P for profitable production in Brazil and elsewhere in the tropics is whether this P can be sufficiently mobilized to meet crop P demand, and over what time period this residual

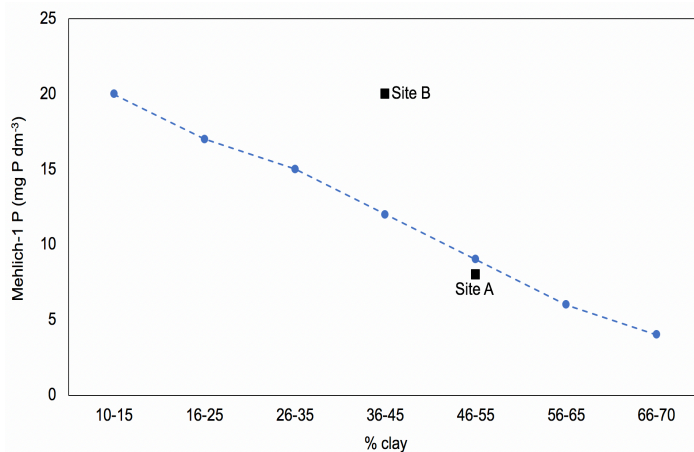


Figure 2.1. Critical Mehlich-1 phosphorus levels by % clay group in the Brazilian Cerrado (dashed line; de Sousa and Rein, 2011) and mean values for Sites A and B in this study.

soil P can be used to support crop production.

Soil indicators, such as soil test P (STP) (e.g., Mehlich-1 P or Bray-1 P) or labile P (e.g., P extracted by NaHCO_3 in the Hedley fractionation scheme), are commonly used to approximate

the plant-availability of P in cropland soils (Hedley et al, 1982). Critical levels for STP have been established in many cases, and these critical levels can vary based on soil texture. For example, de Sousa and Rein (2011) report critical levels of Mehlich-1 P ranging from 4-20 mg P dm^{-3} for soils in different % clay groupings in the Brazilian Cerrado (Figure 2.1), and state that fertilization can be reduced by half once Mehlich-1 P exceeds the critical level appropriate for a given soil texture.

While field trials to establish critical STP levels are relatively common, far fewer studies have tested substantially reduced or zero P fertilization following a period of residual soil P accumulation. McCollum (1991) provides a detailed account of 8 years of annual P fertilizer additions and residual soil P accumulation followed by cessation of fertilization and monitoring of STP and yield response for 18-26 years on a fine sandy loam under corn-soybean rotation in North Carolina, USA. Results from that study indicated that soils with high STP due to residual soil P accumulation could remain above yield-limiting STP levels for approximately one decade following the termination of fertilization. Eghball et al. (2003) also observed that cessation of P inputs with continuing corn harvest can reduce high STP levels while maintaining yields for multiple growing seasons in Nebraska, USA. Both studies found that the rate of STP decrease without fertilizer application was greater when initial STP was greater (McCollum, 1991; Eghball et al., 2003).

A paucity of similar field evidence exists for tropical soils under surplus fertilization for many years that shows yield response to reduced or zero P fertilization treatments, in part because these soils have typically been in intensive crop production for a shorter duration than in the USA or Europe. Furthermore, the rate of increase in STP with surplus fertilization of soybean fields can be much slower in Brazil's high P-fixing soils than soils with more inherent fertility in the US (Roy et al., 2017). Better understanding of residual P accessibility in high P-fixing soils is important for both phosphorus stewardship broadly and farm economics (e.g., fertilizer accounts for a substantial fraction of operating costs in Mato Grosso; Meade et al., 2016). To help fill

this knowledge gap, we asked the following questions regarding the accessibility of residual soil P in Oxisols under soybean production in Mato Grosso, Brazil:

- Does a single season of reduced or zero P fertilization affect the productivity of soybean in medium textured Brazilian Oxisols that have received surplus P fertilization for a decade?
- Does texture (i.e., % clay) influence the effect of treatment on yield response?
- What changes in STP can be observed across treatments between planting and post-harvest?

2.2. Materials and Methods

2.2.1 Study Area

The study took place during the 2018-2019 harvest season at Fazenda Tanguro, a farm located at the intersection of the Amazon and the Cerrado in the state of Mato Grosso, Brazil. The precipitation regime at Fazenda Tanguro follows the typical wet and dry seasonality that dictates management across Mato Grosso. On average, total annual precipitation on the farm is a mean of 1800 mm, the majority of which falls during the wet season (Nov-April). Soybean is planted in early November and harvested Feb/March. For double-cropped fields, corn is directly seeded (no-till) immediately after soybean harvest.

Two experimental sites (Figure 2.2) were identified on opposite ends of the same field that are characterized by different soil textures. The field was first deforested and converted to pasture in 1990, planted with soybeans in 2009, and has been double-

cropped as soybean/corn since 2015. The range in soil textures found across this particular field is attributed to an adjacent riparian zone that exposes the landscape to hydrologic mechanisms that are hypothesized to affect soil characteristics that have otherwise developed over geologic time scales. The two sites have % clay values of 53% (Site A) and 42% (Site B), falling in the middle of the wide range of soil textures measured across Mato Grosso croplands (7-71 % clay) by Roy et al. (2017).

2.2.2 Experimental Design

Both of the sites were arranged in a randomized block design with five replications under three P treatments: 0%, 50%, and 100% of P fertilizer (N-P-K: 0-27-9) historically applied to the replace on an annual basis field ($87 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1} \text{ yr}^{-1}$, or $38 \text{ kg P ha}^{-1} \text{ yr}^{-1}$) (Figure 2). Mineral P fertilizer (0-27-9) was broadcast across

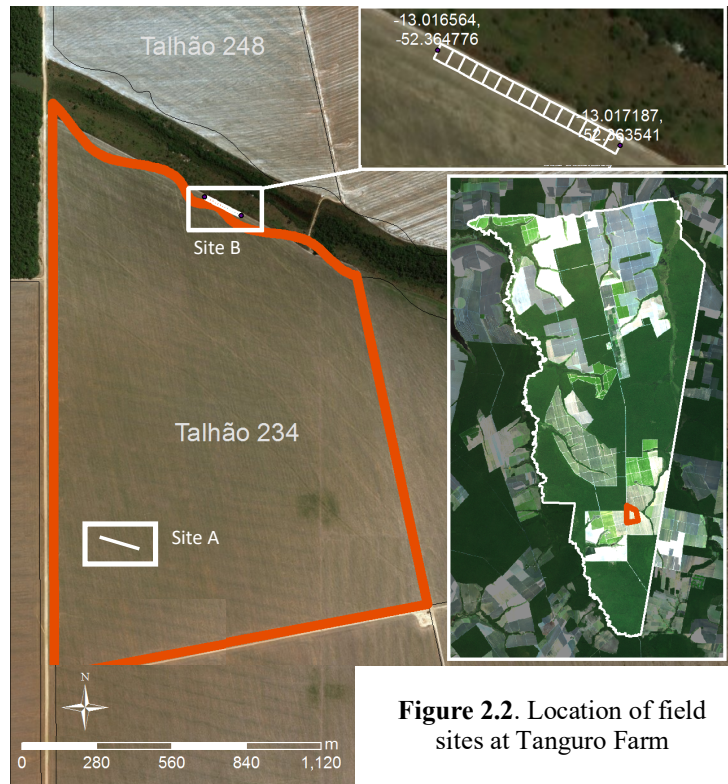


Figure 2.2. Location of field sites at Tanguro Farm

10x12 m plots ($n = 30$) by hand within several days of planting. For all reduced and zero P treatments, solid KCl was broadcast in accordance with standard potassium management (25 kg K ha^{-1}) on the farm. All other management practices prior to harvest

(liming, tillage, pesticide application and desiccation) remained consistent with the farm's typical management schedule.

2.2.3 Soil Sampling

Soil was sampled prior to fertilization and planting for characterization, as well as post-soybean harvest to observe STP changes for each plot. Samples were collected at depths of 0-10, 10-20, and 20-30 cm and were composited from three random locations across each plot. A non-composited sample of the 30-50 cm horizon was collected for each plot to confirm findings reported by Riskin et al. (2013) that suggested a lack of vertical P flow below the plow layer. Bulk density (BD) for each horizon was averaged ($n = 2$) between values measured from pits located randomly within the bounds of each experimental site.

2.2.4 Soil Characterization and Phosphorus Metrics

All soil samples ($n = 120$) were tested for physical and chemical attributes at the soils lab in Escola Superior de Agricultura "Luiz de Queiroz" (ESALQ) at the University of São Paulo in Brazil, including soil texture (sand/silt/clay), pH, organic matter, cation exchange capacity, total exchangeable bases, base saturation, potential acidity, aluminum saturation, and Mehlich-1 P. The 0-10 and 10-20 cm layers were composited for each plot ($n = 30$) and analyzed for total P, Al_2O_3 , Fe_2O_3 , and SiO_2 by lithium borate flux fusion digestion and X-ray fluorescence in Reno, NV by ALS Chemex.

Extractions for Bray-1 P (Frank et al, 1998), oxalate-extractable P, Fe, and Al (McKeague and Day 1966), and P sorption index (PSI) (Bache and Williams, 1971) were conducted in the Terrestrial Biogeochemistry Lab at Brown University. Bray-1 P was extracted with a solution comprised of 0.03 *M* NH₄F and 0.025 *M* HCl that was shaken with air-dry soil (sieved to 0.25 mm) for 5 min at a soil:solution ratio of 1:10, centrifuged for 10 min (4460 x g), filtered (0.45 µm) and P was measured by colorimetric analysis (D'Angelo et al, 2001). For determination of degree of P saturation (DPS), P, Al, and Fe were extracted using a mixture of ammonium oxalate solution (0.2 *M*) and oxalic acid solution (0.2 *M*) of which 15 mL was shaken with 0.25 g of ground (< 0.15 mm) air-dried soil for 4 hr in the dark, centrifuged for 10 min (4460 x g), and filtered (0.45 µm). Oxalate extractable P, Al, and Fe (i.e., Ox-P, Ox-Al, Ox-Fe) were measured from extracts using inductively coupled plasma atomic emission spectroscopy. DPS was then calculated from these results as suggested by Nair et al (2004), such that:

$$DPS (\%) = \frac{OxP}{0.5 (OxFe + OxAl)} \times 100$$

To calculate PSI (L kg⁻¹ of soil), an incubation was conducted for each sample on one gram of air-dried soil (sieved to 0.25 mm) that was shaken with 20 mL of a solution containing 75 mg P L⁻¹ (0.01 *M* CaCl₂ solution mixed with KH₂PO₄) for 24 hours. The soil solution was then centrifuged for 10 minutes (4460 x g), filtered (0.45 µm) and measured for orthophosphate by colorimetric analysis. PSI was calculated based on incubation results, such that:

$$PSI = \frac{S}{\log (C_e)}$$

where S is the amount of P sorbed during the incubation experiment (mg P kg^{-1} soil) and C_e equals the concentration of P in the final equilibrium solution (Bache and Williams, 1971). Taking advantage of the regression model developed from batch experiment results conducted by Roy et al. (2017), PSI values were used to calculate remaining sorption capacity (S_{rem} , $\text{mg P kg dry soil}^{-1}$) as:

$$S_{rem} = 1.2682 \cdot PSI + 129.72$$

Measured results for S_{rem} , TP, and Bray- P_1 were then compared to calculated values predicted by the regression models developed by Roy et al. (2017).

2.2.5 Yield Sampling and Analysis

Biomass was harvested by hand and cut approximately 6 cm above the ground to mimic what is removed by the combine. Biomass was sampled at 10 m row lengths and composited from two random locations within each plot to represent 1/100th of a hectare. Biomass samples were air-dried and weighed prior to threshing, the process of extracting the grain from the plant. After threshing, total grain from each sample was weighed and sub-samples of both the grain and biomass were oven-dried to measure the moisture content of each. Wet mass of total plant matter was assumed to be the difference between the total biomass measured prior to threshing and the total grain measured just after threshing. Dry masses were calculated based on % moisture results for the grain and plant matter of each sample.

Yield performance for each plot was defined as mean dry grain produced per plant, calculated from the plant count and total dry grain value of each sample. Addition

to residual P stocks (kg P ha⁻¹) was calculated based on mass P inputs and P outputs per area. Justified by findings reported by Riskin et al. (2013b) and Neill et al. (2017), P lost via leaching or overland flow was assumed to be negligible and therefore excluded from P outputs. P inputs were defined as applied P fertilizer (kg P ha⁻¹) and P outputs (kg P ha⁻¹) were calculated based on harvested biomass and measured P concentrations, such that

$$P_{out} = [(P_{grain} \cdot m_{grain}) + (P_{plant} \cdot m_{plant})] \times 1000$$

where P_{grain} and P_{plant} represent g P per kg of dry mass for the grain and plant matter of each sample (analyzed by ESALQ), and m_{grain} and m_{plant} represent dry mass per area (kg dry biomass ha⁻¹) of grain and plant matter, which were calculated from dry masses per plant and the standard plant densities (plants ha⁻¹) known based on equipment row and plant spacing. Actual plant densities were measured in the field and found comparable to standard plant density for the site with higher clay content (Site A), but almost double the standard plant density for the site with lesser clay content (Site B). This difference was attributed to an inconsistent planting density at the edge of field where Site B was located. Plant density did not influence yield performance per plant; a lack of correlation was confirmed by simple linear regression analysis (0%: $r^2 = 0.012$, $p = 0.860$; 50%: $r^2 = 0.019$, $p = 0.825$; 100%: $r^2 = 0.176$, $p = 0.481$). It was therefore assumed that yield performance was consistent on a per plant basis for each treatment regardless of planting density. The P budget (kg P ha⁻¹) was calculated using standard plant densities and yield measured per plant to compare residual P for each treatment and site.

2.2.6 Statistical Analysis

To first confirm known correlations between initial soil conditions that characterize the dynamic mechanisms of P-fixation in tropical soils, a Pearson correlation matrix was developed for all physical and chemical attributes measured prior to treatment.

Next, a statistical analysis was conducted to analyze yield and STP response to two categorical variables; treatment and texture. Prior to analysis, relevant soil characteristics were statistically tested to confirm uniformity within each site. This eliminated the possibility that yield and STP responses within each site could have been skewed by a lurking variable other than treatment (i.e., initial conditions). The null hypotheses tested by a 1-way ANOVA (Glantz, 1990) for each site (A, B) were

$$\begin{aligned} X_i [0_{\text{mean}}, A] &= X_i [50_{\text{mean}}, A] = X_i [100_{\text{mean}}, A] \\ X_i [0_{\text{mean}}, B] &= X_i [50_{\text{mean}}, B] = X_i [100_{\text{mean}}, B] \end{aligned}$$

where the variable X_i was tested for % clay, %R₂O₃, %SiO₂, initial STP (Bray-P₁, Mehlich-P₁), and PSI. A Shapiro Wilk test was used to confirm normal distribution of each treatment group for each plot ($n = 5$). To justify 'texture' as a categorical variable that identifies distinguishable initial P sorption metrics between the two sites, these same values were tested under the following null hypotheses to confirm relevant initial conditions are in fact statistically different between sites using a t-test.

$$\begin{aligned} X_i [A, 0-10 \text{ cm}] &= X_i [B, 0-10 \text{ cm}] \\ X_i [A, 10-20 \text{ cm}] &= X_i [B, 10-20 \text{ cm}] \end{aligned}$$

A Shapiro Wilk test was used to confirm normal distribution of each variable for all plots within each experimental site ($n = 15$). Mann-Whitney U was applied for comparisons in

cases where data did not result in a normal distribution. Because these hypotheses were all rejected ($p < 0.05$), soils from each site were considered significantly different with regard to texture and relevant P metrics, despite shared land use history. Soil texture was therefore treated as a categorical variable; sites were identified as having more (Site A) or less (Site B) % clay.

A two-way ANOVA was applied to compare yield response (Y; dry grain mass per plant) to different treatments (0, 50, 100 %) between each soil texture (A, B), such that the following null hypotheses were tested:

$$\begin{aligned} Y [0, A] &= Y [50, A] = Y [100, A] \\ Y [0, B] &= Y [50, B] = Y [100, B] \\ &\text{and} \\ Y [0, A] &= Y [0, B] \\ Y [50, A] &= Y [50, B] \\ Y [100, A] &= Y [100, B] \end{aligned}$$

The same two-way ANOVA conducted for yield response was applied for the change in STP across treatments and textures. For all multiple comparisons, Cooke's distance and DFBETAS were used to screen for outliers and a post-hoc TUKEY HSD was ran to compare differences between treatments.

2.3. Results

2.3.1 Texture as a Variable

Texture was defined as a categorical variable to illustrate distinguishing soil characteristics between the two experimental sites (A, B). Texture is not an exclusive indicator of yield response to P treatments, however categorizing the experimental sites

based on texture (and metal oxide content) corresponded to P metrics (STP, DPS, S_{rem}) that have been used to predict yield response to reduced or zero P fertilization in past studies. Though similarly textured with respect to the wide range found across Mato Grosso (Roy et al., 2017), average initial Bray-P₁ STP in the upper plow layer (0-10 cm) on Site A with greater clay content (54% clay) was nearly quadruple the value found on Site B (42% clay) adjacent to the riparian zone. Significant differences were detected for clay content, metal oxide concentration, and STP (Mehlich-P₁ and Bray-P₁) between the two sites (Table 2.1). To capture these differences, texture was defined as a categorical variable that distinguished the two experimental sites (i.e. more or less bioavailable P).

	Site A	Site B	<i>p</i> -value
Clay (0-10 cm)	53.7	41.0	1.35E-09
Clay (10-20 cm)	53.4	42.3	1.29E-08
Clay (20-30 cm)	57.7	46.6	4.80E-08
Bray (0-10 cm)	16.4	58.8	9.54E-13
Bray (10-20 cm)	9.5	29.4	7.72E-08
Bray (20-30 cm)	2.3	7.3	4.27E-05
SiO₂ (0-20 cm)	59.1	66.9	2.20E-16
Al₂O₃ (0-20 cm)	21.4	18.2	4.16E-12
Fe₂O₃ (0-20 cm)	4.4	2.2	2.20E-16

Table 2.1 Mean values for Site A and B and respective *p*-values from *t*-tests applied between sites for % clay and initial STP (mg P kg⁻¹) by horizon as well as % metal oxide contents of the plow layer.

There were no significant differences found between treatments within each site for the characteristics defined above. Variable yield response within each site was thus assumed to be a consequence of treatment. Variable yield response between sites for each treatment was assumed to be a consequence of P metrics and soil characteristics associated with texture.

2.3.2 Physical and Chemical Soil Attributes

Plow Layer	Site A	Site B	MT (min)	MT (max)	Units
Clay	54	42	8	71	%
Sand	43	56	24	84	%
OM	22	20	18	40	g dm ⁻³
pH	6	6	-	-	n/a
Bray P	13	44	12	64	mg P kg ⁻¹ soil
Mehlich P	7	13	2	47	mg dm ⁻³
TP	263	286	108	487	mg P kg ⁻¹ soil
SiO ₂	59	67	34.7	88	%
Al ₂ O ₃	21	18	4.4	30.9	%
Fe ₂ O ₃	4.4	2.2	2.2	13	%
DPS	3.5	6.4	0	17	%
Srem	615	597	306	918	mg P kg ⁻¹ soil
K	79	96	-	-	mg dm ⁻³
Ca	2.9	3.5	1.05	2.84	cmolc dm ⁻³
Mg	1.2	1.7	-	-	cmolc dm ⁻³
Al	0.1	0.1	-	-	cmolc dm ⁻³
Potential acidity	2.5	2.1	-	-	cmolc dm ⁻³
Total Bases	4.3	5.4	-	-	cmolc dm ⁻³
CEC	6.8	7.6	-	-	cmolc dm ⁻³
Base Saturation	63	72	28.9	61.3	%
Al saturation	2.4	1.4	0.9	18.5	%

Table 2.2 All physical and chemical attributes for Sites A and B were averaged between the 0-10 horizon and the 10-20 horizon to characterize the plow layer (0-20 cm). Minimum and maximum values reported by Roy et al. (2017) based on 24 soybean plots of varying ages were used to represent the range of soil characteristics across Mato Grosso, Brazil.

A simple linear regression ($r^2 = 0.86$) between clay content and R_2O_3 confirmed texture to be a valid proxy for the mineral composition that is believed to dictate mechanisms of soil P bioavailability. The relevance of R_2O_3 was confirmed by strong correlations observed with initial STP (Bray-1; $r^2 = 0.87$, Mehlich-1; $r^2 = 0.75$) and DPS ($r^2 = 0.79$). There was surprisingly no correlation between R_2O_3 and S_{rem} , likely due to the limited range in R_2O_3 under observation for this study compared to the spectrum of soils that were analyzed by Roy et

al. (2017) across Mato Grosso.

However, values predicted for S_{rem}

using the multiple linear

regression models (a function of

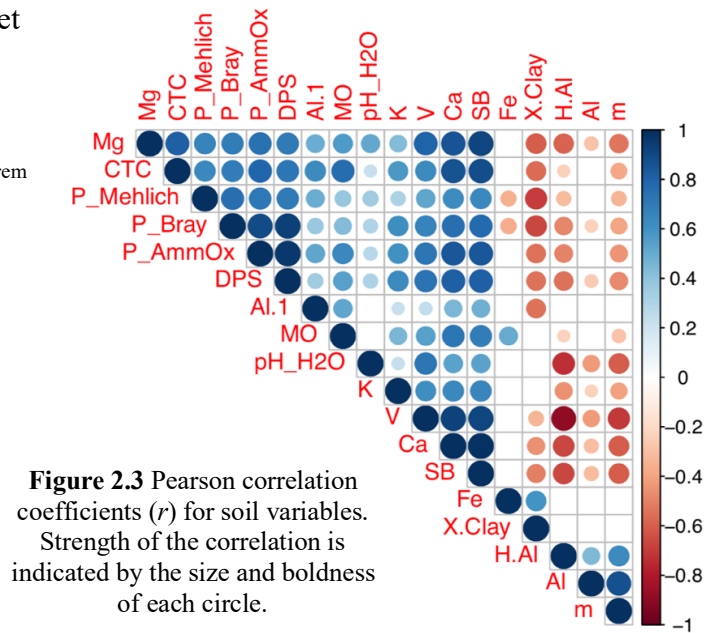
R_2O_3 and years in development)

proposed by Roy et al.

(2017) did compare well to

S_{rem} values calculated based

on measured PSI.



Relationships between physical and chemical soil attributes were gleaned from a Pearson Correlation matrix, visually presented below as a correlogram (Fig 2.3). As expected, clay content shows strong negative correlation to available STP metrics, cation exchange capacity and base saturation, though no correlation to aluminum saturation. Iron content was weakly correlated to clay content and OM.

In agreement with soil characteristics reported by Roy et al (2017), cation exchange capacity was strongly correlated with organic matter (Fig 2.2). There was a significant difference found between average OM values for each site, such that Site A was characterized by greater OM and clay content, however across all 30 plots, OM did not correlate to % clay content as suspected. Though Site A was characterized by a greater mean value of OM, DPS and CEC at site A were less than site B; mean values between sites contradict the correlation observed between DPS, CEC and OM (Fig 2.2).

2.3.3 Yield Response

ANOVA (2-way) analysis of yield (dry grain mass per plant) response to both treatment and texture revealed no significant differences due to either variable independently (treatment: $p = 0.25$, texture: $p = 0.26$). There was a significant difference detected for the interaction between the two variables ($p = 0.047$), though post-hoc results suggested that treatment did not result in significantly different yields for either site. Boxplots suggested extreme values may be strongly influencing the results of the post-hoc tests, therefore Cook's Distance and DFBETAS were calculated to screen for outliers. The removal of two plots identified as outliers from each site's dataset prior to running a 2-way ANOVA resulted in significant differences between yield due to texture ($p = 0.007$), treatment ($p = 0.002$), and the interaction between the two ($p < 0.001$). Therefore, caution should be used in interpretation of the results using all 30 plots.

The post-hoc TUKEY HSD analysis revealed a significant difference between the 0 and 100 treatment on site A and no significant differences detected between treatments on site B (Table 2.3). Though both sites are considered to be medium textured Oxisols, these results suggest that even relatively small differences in soil

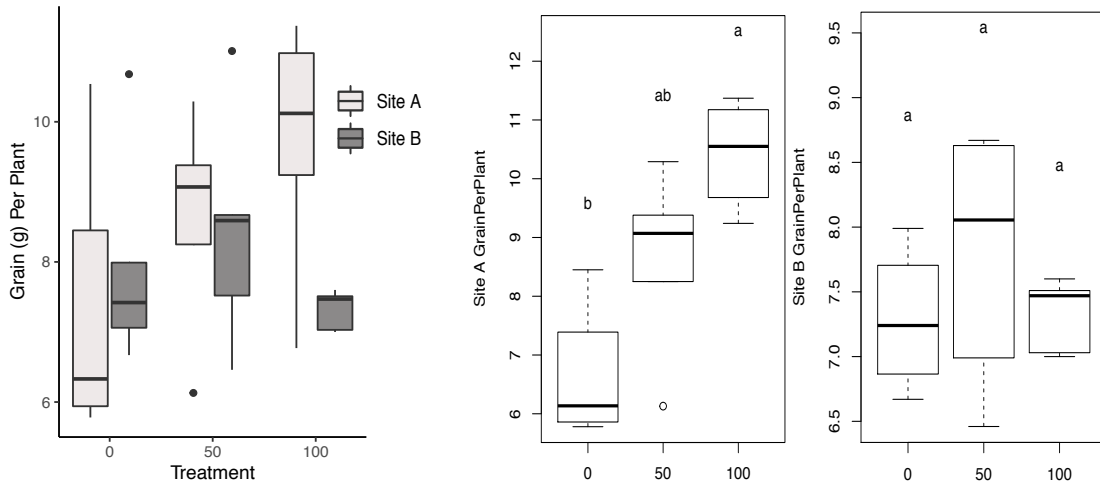


Figure 2.4 (a) Yield response (n=30) grouped by treatment and texture. Post-hoc TUKEY results after screening outliers (n=26) for site A **(b)** and B **(c)**. Letters indicate significant differences or lack thereof.

texture and relevant soil P metrics may indicate a nuanced response to reduced P application. Site A

showed a noticeable trend of

reduced median yield response to reduced P application, though yield performance at site B appeared unaffected across all treatments (Fig 2.3a).

	Site A		Site B	
Comparison	n=30	n=26	n=30	n=26
0 % vs 50 %	0.561	0.107	0.839	0.533
0 % vs 100 %	0.160	0.006	0.739	0.996
50 % vs 100 %	0.635	0.151	0.412	0.546

Table 2.3 Post-hoc TUKEY HSD p-values between treatments both including and excluding identified outliers.

Under standard fertilization, the less P saturated (i.e. low DPS) site (A) outperformed the more P saturated (B) site significantly ($p = 0.043$). Though not significantly different, mean yield from Site A (8.62 g per plant) was slightly higher than Site B (8.45 g per plant) under 50% P, but under zero P, Site B (7.96 g per plant)

outperformed Site A (7.41 g per plant). Mean yield results for reduced and zero P suggest that the greater bioavailable P pool observed from initial STP metrics in Site B may have provided a greater P source in the absence of P fertilization than that of Site A. These results further support guidelines offered by EMBRAPA (de Sousa and Rein, 2011), such that Site B was unaffected by reduced and zero P fertilization and it tested well above the recommended critical STP threshold (Mehlich $P_1 > 12 \text{ mg dm}^{-3}$; Figure 2.1).

In response to the questions posed by this study, these results suggest that reduced or zero P fertilization can significantly affect soybean yield across medium textured Oxisols that have been P fertilized for a decade, and how treatment affects yield response is variable for different textured Oxisols within a medium range.

2.3.4 Change in STP

The vertical distribution of the observed change in STP (Fig 2.5) are in line with findings from Riskin et al. (2013) that indicated negligible vertical P flow below the plow layer. These results also suggest that bioavailable P stored within the plow layer acted as a greater P

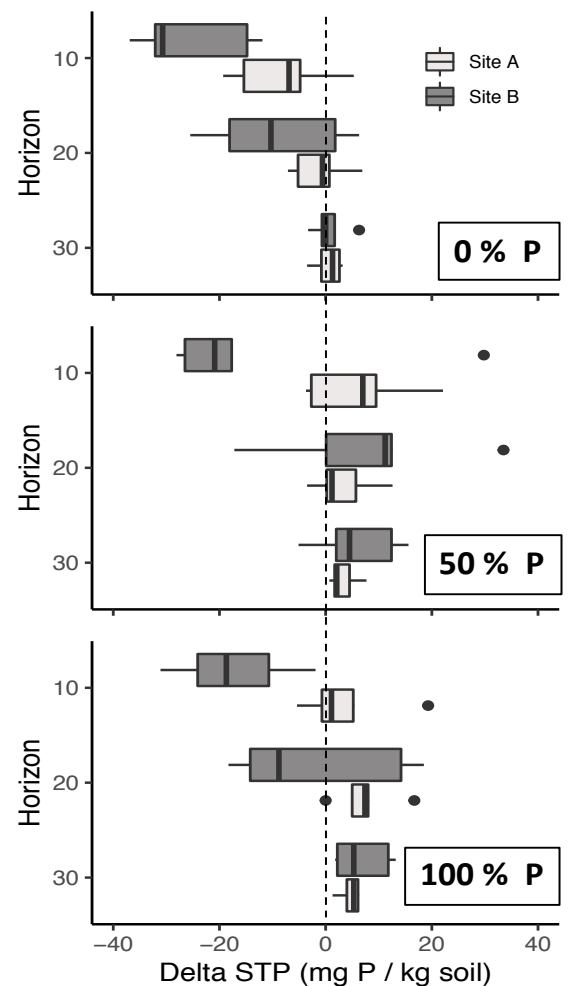


Figure 2.5 Change in Bray STP ($\text{mg P kg}^{-1} \text{ soil}$) from planting to harvest for each soil, grouped by horizon and site for each treatment.

source for site B than for site A in the absence of standard P fertilization, primarily sourced from the top 10 cm of the soil profile.

2.3.5 Residual P

The P balance calculated under standard fertilization treatments (100%) (Table 2.4) followed a similar trend reported from previous studies resulting in an average of 40% P use efficiency (Riskin et al, 2013; Roy et al, 2016). P use efficiency

was improved under reduced (50%) fertilization rates, such that 78% of applied P was consumed by the plant. Change in residual P was negative under the zero (0%) treatment given that harvested P was sourced exclusively from P stocks stored in the soil.

Site	kg P ha ⁻¹		
	Applied	Harvested	Residual
A	0	12.2	-12.2
A	19	14.7	4.3
A	38	17.2	20.8
B	0	13.7	-13.7
B	19	14.9	4.1
B	38	13.0	25.0

Table 2.4 Calculated change in residual P (added or removed) per hectare. Harvested P was calculated from P harvested per plant and the standard planting density.

2.4. Discussion

Yield performance under reduced (50 %) P on Site B support recommendations from EMBRAPA that suggest mineral P application can be reduced by half without compromising yields if STP is measured above a critical STP threshold. Though yield was not significantly different from the standard, there was a noticeable risk of decline in yield when reducing P inputs on Site A, which measured just below the critical STP (Mehlich-P₁ = 9 mg dm⁻³). Furthermore, this study confirmed the critical role of texture with regard to yield response to P treatment, such that texture can be considered a defining characteristic to categorize nutrient budgeting, even for regional variability of a single soil classification (e.g., Oxisols in Mato Grosso). Compromised yield response to

zero P input on Site A suggested that 10 years of surplus fertilization and residual P build up on soils with a high capacity for P-sorption will not support soybean production in the absence of applied P. The lack of risk associated with the zero P input on Site B highlights the opportunity for a more reformed set of guidelines that includes STP thresholds in which P can be reduced by more than 50% to maintain soil fertility and thereby conserve money and P resources.

The post-hoc TUKEY HSD results confirmed findings from Dodd and Mallarino (2005) that concluded texture to have more of an effect on yield than treatment. The results from this study indicate that management opportunities for reduced P application will demand variable solutions informed by yield trials across a wider range of Oxisols across Mato Grosso. The conclusions from this field study are limited to medium textured soils and do not capture the full range of soil conditions that exist across the agricultural landscape in Mato Grosso, Brazil (Roy et al., 2017).

The results from this study also support conclusions drawn by Ker et al (1996) that suggest mineral quality and type to be a more accurate indicator of P sorption capacity than texture. Long-term field trials would not only benefit to capture a wider range of textures but also a greater variation of R_2O_3 concentrations to observe rates of decline for remaining P sorption over time with respect to mineralogy. Across a wide range of textures, the clay content of Oxisols is typically used as a proxy for the concentration of R_2O_3 , which is expected to correlate with OM content. The presence of OM can potentially function to occlude sorption sites and decrease remaining P sorption capacity, however P sorption capacity is driven by R_2O_3 concentration (de Campos et al,

2016). The oppositional mechanisms of clay associated soil characteristics confirms the critical relevance of mineral composition with respect to P sorption.

Contradicting correlations observed within this study between clay content, R_2O_3 concentrations and OM content emphasized the nuanced dynamics relevant to medium textured Oxisols. Greater variability in yield response across replications for each treatment within Site A compared to Site B is hypothesized to reflect a greater impact of CEC, OM, and base saturation on the accessibility of residual P when bioavailable P is more limited, such as the conditions on Site A. This study was not designed to explore P desorption from metal oxides (R_2O_3) stimulated by OM, though findings from long-term field trials in Brazil emphasize microbial activity as an opportunity for accessing soil P (Rigo et al, 2019). Advanced biochemical analyses of soil attributes paired with yield response to mineral P cessation could also offer a broader scope of management opportunities to access the stable fraction of residual P.

With regard to the sustainability of agricultural intensification in the tropics, a critical question remains: is it possible to reduce P fertilizer without compromising yields beyond one harvest season? Temporal variations in STP reduction from long-term P cessation highlighted by Zicker et al. (2018) demands further exploration in tropical environments to consider long-term consequences. The opportunity to reduce P consumption in a single year will economically benefit farmers when the cost of P has temporarily spiked. Whether tropical producers can afford to reduce P inputs beyond a single year holds major implications for the sustainability of intensification in the tropics. In agreement with Bruulsema (2019), this study highlights the need for long-term field

trials across varying latitudes and textures, specifically in the tropics, to better inform management practices aimed at P-use efficiency.

CHAPTER 3. CONCLUSION & MANAGEMENT OPPORTUNITIES

The experimental results from this study confirm the relevance of texture as a variable that informs management opportunities for the soy industry in Brazil.

Though categorized by texture, mineral P application recommendations based on critical STP thresholds (de Sousa and Rein, 2011) are generous compared to the findings from this study. Recommendations could be refined to incorporate reduced ‘maintenance’ rates below 50% of standard fertilization, including zero P application.

Despite research-informed recommendations, farmers have not adopted this strategy as they have with other practices of conservation agriculture, such as no-till. The scarcity of tropical yield trials across variable textures beyond the ‘corrective’ stage of fertilization presents an opportunity for collaboration between farmers, extension agencies, and researchers to explore strategies for long-term agricultural intensification in the tropics. In this context, the historically developed agricultural industry of Brazil is a fruitful frontier to set a global precedent for strategic research in response to anticipated trends of agricultural intensification in the tropics.

The effective impact of this study is enhanced by the direct relevance of this work to the farm in which the experiment was conducted. Strategies of conservation agriculture have been adopted previously for soybean cultivation at Tanguro farm, such as no-till and double cropping. These practices coupled with reduced mineral P

application create potential to enhance P use efficiency due to biological influences (Rosa et al, 2019; Margenot et al, 2017; Salton et al, 2011). Practices that enhance P use efficiency provide economic benefits for farmers as well as reduced risk of environmental degradation, which becomes a greater threat above critical STP thresholds, and P resource scarcity.

Amaggi, the production company that manages Tanguro farm, is well poised to be a leader in conservation agriculture by trialing and normalizing P cessation, such as Herbert Bartz who stimulated the no-till movement (De Freitas & Landers, 2014). Reduced P application does not require advanced equipment, though it does require detailed analyses of the soils, a feasible expense for a farm the size of Tanguro. Mineral P reduction at Tanguro alone could notably affect global P consumption; the amount of mineral P imported to fertilize Tanguro's operation (calculated to be ~ 3491 tons P yr⁻¹) is comparable to the amount of P imported into the state of Vermont (calculated to be ~ 3249 tons P yr⁻¹) as feed and fertilizer (Wironen et al., 2018).

Consistent annual soil tests in accordance with the adoption of P reduction strategies may build farmer confidence in the texture-based recommendations proposed by EMBRAPA. This extent of detailed soils analyses is more feasible for agro-industrial operations, which have a platform to influence regional perceptions regarding P reduction. Findings from this study support concerns regarding the thoroughness of using Mehlich-P₁ testing versus Bray-P₁, or STP and texture testing alone, to inform P management with precision (de Sousa et al., 2010). For farms that don't have access to

detailed geochemical analyses, P metric models based on farm history and texture could begin to be developed based on long-term agronomic yield trials.

Future yield trials that inform long-term P cessation on soy cultivated Oxisols may also benefit to couple reduced P with integrated crop-livestock (ICL) as isolated and paired treatments to evaluate the synergistic potential between these two developing strategies in nutrient management (Faccio Carvalho, 2010). The sustainability of long-term soybean intensification in the tropics relies on innovative strategies such as no-till, ICL and informed P management to support economic viability and minimal impact to watershed health and the native ecosystems of the Amazon and the Cerrado.

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